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Comparison of Liquid Swine Manure and Aqua-Ammonia Nitrogen Application Timing on Subsurface Drainage Water Quality in Iowa

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Abstract. *In Iowa and many other Midwestern states, excess water is removed artificially through subsurface drainage systems. While these drainage systems are vital for crop production, nitrogen (N), added as manure or commercial fertilizer, or derived from soil organic matter, can be carried as nitrate-nitrogen (NO_3-N) to downstream water bodies. A five-year, five-replication, field study was initiated in the fall of 1999 in Pocahontas County, Iowa, on 0.05 ha plots that are predominantly Nicollet, Webster, and Canisteo clay loams with 3% to 5% organic matter located on glacial till within the Des Moines Lobe. The objective was to determine the influence of seasonal N application as ammonia or liquid swine manure on flow-weighted NO_3-N concentrations and losses in subsurface drainage water and crop yields in a corn-soybean rotation. Four aqua-ammonia N treatments (168 or 252 kg N ha^{-1} applied for corn in late fall or as an early season side-dress) and three manure treatments (218 kg N ha^{-1} for corn in late fall or spring or 168 kg N ha^{-1} in the fall for both corn and soybean) were imposed on subsurface-drained, continuous flow-monitored plots. Precipitation during the drainage season (March to November) was slightly below the long-term norm (722 mm) for all four years in the study period and ranged from 615 mm in 2001 (85% of normal) to 707 mm (98% of normal) in 2004. Monthly rainfall was highly variable, and subsurface drainage, or the lack thereof, usually mimicked the precipitation patterns. On average, 69% of subsurface drainage occurred in May and June of each year, with lower amounts in April and July. Four-year average flow-weighted NO_3-N concentrations measured in drainage water were ranked: spring aqua-ammonia 252 (23 mg L^{-1}) = fall manure 168 every year (23 mg L^{-1}) > fall aqua-ammonia 252 (19 mg L^{-1}) = spring manure 218 (18 mg L^{-1}) = fall manure 218 (17 mg L^{-1}) > spring aqua-ammonia 168 (15 mg L^{-1}) = fall aqua-ammonia 168 (14 mg L^{-1}). Corn yields were significantly greater ($p = 0.05$) for the spring and fall manure 218 rates than for non-manure treatments. Soybean yields were significantly greater ($p = 0.05$) for the treatments with a spring nitrogen application to the previous corn crop. Overall, under the slightly dry to normal precipitation conditions of this study, corn yields and NO_3-N concentrations in subsurface drainage were not significantly different ($p = 0.05$) between fall and spring treatments at the 168 aqua-ammonia or 218 kg ha^{-1} N manure N rates.*

Keywords. *Leaching, Nitrate, Nutrient management, Subsurface drainage, Water quality.*

The use of artificial subsurface drainage systems is critical for crop production in many areas of Iowa and other Midwestern states. These drainage systems allow for timely seedbed preparation, planting, and harvesting, and they protect crops from extended periods of saturated soil conditions. However, installation and use of these subsurface drainage systems has increased the loss of nitrate-nitrogen (NO_3-N) to downstream water bodies (Gilliam et al., 1999). The movement of NO_3-N from agricultural fields to drainage waters is a concern for nonpoint-source pollution of surface waters and ultimately the Gulf of Mexico, where it has been implicated as a contributor to the formation of a hypoxic zone (Mitsch et al., 2001; Rabalais et al., 1996). NO_3-N export to downstream water bodies from a given area depends on the agronomic practices implemented as well as site, soils, and climatological factors. As a best management practice, N should be applied at the correct rate nearest to the time it is needed by the crop. Typically, soil conditions, fertilizer cost, equipment, and labor favor fall or early spring application in the upper Midwestern U.S. (Dinnes et al., 2002; Randall and Schmitt, 1998). Risk of N leaching loss due to excess precipitation in the fall and/ or spring of the year as well as the possibility of N loss due to denitrification has led to the conclusion that fall application of manure or fertilizer N is agronomically, if not environmentally, risky. A review of research (Bundy, 1986) indicated that fall applications of ammonium (NH_4) based N fertilizers are usually 10% to 15% less effective than spring applications. Similar results were reported in a separate study in southern Minnesota (Vetsch and Randall, 2004), indicating that spring applications are generally superior to fall for corn production. Other research has also emphasized that March through May precipitation is a major cause of N loss from fertilized fields of spring-planted annual crops such as corn and soybean since this period is prior to the rapid growth and N

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uptake period (Balkcom et al., 2003; Randall et al., 2003; Randall and Vetsch, 2005). Randall et al. (2003) and Randall and Vetsch (2005) found in a study in southern Minnesota that NO_3-N losses in subsurface drainage from a corn-soybean rotation were reduced 13% to 14% by applying N in the spring rather than the fall.

The increasing concentration of livestock production into larger facilities in the U.S. creates a need for proper disposal of large volumes of manure, typically in liquid form. The majority of manure in the Upper Midwest is applied to corn. Producers are faced with limited receiver land that is located near large facilities, creating the concern of overapplication (Schmitt et al., 1996). Schmitt et al. (1998) proposed a possible solution to the perceived risk to water resources by selecting alternative crops for manure application. In the Upper Midwest, ground planted to soybean as a receiver of manure was a logical choice, as soybean is commonly grown in rotation with corn. Schmidt et al. (2000) reported that postharvest soil NO_3-N amounts (0 to 120 cm) at N application rates of less than 260 kg ha^{-1} on soybean, regardless of source, was less than 70 kg ha^{-1} and may not represent a large environmental risk. Bakhsh et al. (2009) reported an 80% increase in drainage NO_3-N concentrations and 58% increase in drainage NO_3-N loads when manure was applied each year to both corn and soybean, compared to a corn-soybean system when manure was just applied prior to the corn. In this study, the nitrogen application rates from manure averaged 174 and 219 kg N ha^{-1} to corn and soybean, respectively, compared to 177 kg N ha^{-1} to corn only (Bakhsh et al., 2009).

Since there are some practical advantages to early application of fertilizer or manure N depending on the producer's operation, and despite the research that has already been performed, additional information is needed to better understand the environmental and production impacts of fall and spring fertilizer and manure application in the Upper Midwest. In addition, there is a need for evaluating NO_3-N losses when manure is applied to both corn and soybean in a corn-soybean rotation. Thus, the objectives of this study were to determine the effects of fall and spring N applications and manure applications to both corn and soybean on flow-weighted NO_3-N concentrations and losses along with crop yields in a corn-soybean rotation.

Materials and Methods

Research Site and Monitoring Equipment

The field experimental site was located near Gilmore City in rural Pocahontas County, Iowa. It was in Garfield Township at SW 1/4, Section 27, T92N, and R3lW (94° 29′ 45.6″ W, 42° 44′ 52.8″ N). Seventy-five plots were established in 1989 and until 1999 were used for NO_3-N and herbicide leaching studies (Baker and Melvin, 1994; Lawlor et al., 2008). From 1994 through 1999, continuous corn or corn in rotation with soybean were grown using 45 kg ha^{-1} incremental N rates ranging from 45 to 179 kg ha^{-1} applied shortly after planting as 28% urea ammonium nitrogen (UAN). Predominant soils are Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) and Webster and Canisteo (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) clay loams with 3% to 5% organic matter content. These are poorly to somewhat poorly drained glacial till soils with an average slope of 0.5% to 1.5%. Soil samples taken to a depth of 15 cm in April 2000 averaged 7.6 pH and 56 mg kg^{-1} Bray P1 (very high) (Sawyer et al., 2002) for all soils. In April 2003, Bray P1 was 45 mg kg^{-1} in non-manure plots and 51 in manure plots (both very high), and pH was 7.7. The total research area is 4.5 ha, of which 1.75 ha (35 plots) were used for this study. Each of the 35 plots were 0.05 ha (15.2 × 38.0 m). The other 40 plots had treatments not described in this article. Subsurface drainage lines 7.6 m apart were located parallel to the long dimension through the center of each plot and on the borders between plots at a depth of 1.06 m. Subsurface drains at plot borders were installed to help prevent lateral, subsurface drainage flow from adjacent plots. The border drain lines have an outlet to the surface at a remote location. Only the center drainage line was monitored for drainage volume and NO_3-N concentration. Further discussion of the monitoring system and site layout can be found in Lawlor et al. (2008). Corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) were grown in 76 cm wide rows with ten rows of corn and ten rows of soybean in each plot. The reasoning behind combining both crops in rotation within a single, monitored experimental plot stems from previous research and was bolstered by more current research which found that at close to recommended rates of N (150 to 200 kg N ha^{-1}) for corn production in a corn-soybean rotation, NO_3-N losses and concentrations were not significantly different between the corn or soybean years (Weed and Kanwar, 1996; Kanwar et al., 1997; Randall et al., 1997; Zhu and Fox, 2003). This method allowed for determination of the effects of a corn-soybean system, rather than an individual crop.

Precipitation data were collected using a recording tipping-bucket rain gauge (Campbell Scientific, Inc., Logan, Utah) located near the center of the site area. Rainfall patterns at the site were compared to long-term values (a 30-year average from 1971 to 2000) determined from readings at NCDC stations of Pocahontas (COOP ID 136719) and Humboldt (COOP ID 133985), located 19 km west and east of the research site, respectively. Daily reference evapotranspiration (ET_o) was computed using the Penman-Monteith equation following FAO56 (Allen et al., 1998) for the research site vicinity using meteorological data from the Iowa Environmental Mesonet station near Kanawha, Iowa (~60 km northeast of the project site).

As described by Lawlor et al. (2008), plastic drainage lines from each of three individual plots terminated in separate sumps within a 1.2 m diameter aluminum culvert installed vertically in the soil. The drainage water was pumped by a Zoeller model M53 submersible pump (Zoeller Pump Co., Louisville, Ky.) through plastic plumbing fitted with a common plated sprayer orifice nozzle and a 16 mm Trident T-10 water meter (Neptune Technology Group, Inc., Tallassee, Ala.) for flow measurement. Backpressure created by the meter forced a small constant fraction (0.25%) of all the drainage to be diverted through plastic tubing to a 20 L glass sampling bottle. Sampled and metered drainage was then surface discharged some distance away. Flow-weighted drainage samples were collected and volume measurements recorded at times dictated by flow patterns. Typically, after 13 mm of subsurface drainage, sample jars would contain 10 L of water. Subsamples of the water were taken at this point and represented the quality of water that was intercepted under the treated area over the flow period. Samples collected were chilled and stored at 4°C until analyzed. Nitrate-nitrogen analyses were performed in the Agricultural and Biosystems Engineering Water Quality laboratory located on the campus of Iowa State University using the cadmium reduction method with a Lachet Quickchem 2000 Automated Ion Analyzer flow injection system (Lachet Instruments, Milwaukee, Wisc.).

Drainage volumes, NO_3-N concentrations, NO_3-N losses, as well as crop yields were analyzed as a completely randomized design using PROC GLM (SAS, 2009), and means were separated using a least significant difference test at p = 0.05 ($LSD_{0.05}$). Data for the first year of this study (2000) were not included in overall averages and statistical analyses as 2000 was considered a "calibration or transition" year. Drainage, NO_3-N concentrations, NO_3-N losses, and crop yields for this "calibration or transition" year are not included in this article.

Treatment Description and Crop Production

In the fall of 1999, seven treatments were initiated on 35 plots at the site to determine the effect of N source, rate, and application timing on crop yield and subsurface drainage water quality in a corn and soybean (CS) rotation. Again, in each plot, ten rows of corn and ten rows of soybean were present. Two fertilizer N rates (168 or 252 kg ha^{-1}) applied in the spring or fall and liquid swine manure (LSM) applied in spring or fall (218 kg ha^{-1}) for corn production, and fall-applied LSM for both crops in a CS rotation (168 kg ha^{-1}) were randomly distributed in five predetermined drainage volume blocks. Blocking was based on ten years of drainage volume data collected during previous experimentation at the site (Lawlor et al., 2008). Plots with a low drainage-to-annual precipitation ratio were assigned to block one. The same procedure was used to assign plots to blocks two through five, with block five including those plots with the highest drainage-to-annual precipitation ratios. Plots were split into halves, and corn or soybean were randomly assigned to each half the first year; thereafter, they were rotated within the plot. Nitrogen treatments were consistent after the initial randomization, remaining on the same plot each year of the study.

Commercial-grade 28% (26 Baume) aqueous ammonia fertilizer was applied to the corn half of each plot with a conventional knife applicator to a depth of 10 cm in late fall after soil temperatures were <10°C and cooling or in the spring midrow at or closely following crop emergence. Aqueous ammonia (aqua-ammonia) fertilizer use, while not widespread in Iowa or the Midwestern U.S., was used in this study since it would have similar properties as anhydrous ammonia and the application rate could be applied with greater uniformity and accuracy than anhydrous ammonia. The 168 kg N ha^{-1} rate was within the N fertilizer recommendations established by Iowa State University (Blackmer et al., 1997) for corn after soybean. The 252 kg N ha^{-1} rate was used as a non-limiting N rate comparison. For manure, a manure sample was collected and analyzed prior to application to determine injection rates. The manure was applied using a specially designed LSM applicator to ensure uniformity and accuracy of injection (fig. 1). LSM was shank-injected 15 cm deep. The applicator consisted of a 3500 L polyethylene storage tank mounted on a dual walking tandem wheel base. Two PTO-driven, progressive cavity pumps were used to move and meter the swine manure to a set of knives for injection. A separate recirculation pump, to ensure uniformity during application, was also incorporated into the design. Even with this technology, LSM was found to be difficult to apply at a consistent rate each year; however "as applied" rates from manure samples taken during the application were close to target application rates (table 1). All manure samples were analyzed by Iowa Testing Lab (Eagle Grove, Iowa). On average, spring and fall applications were approximately 218 kg N ha^{-1}. This N rate was based on prevailing recommendations (USDA-SCS, 1992) that approximately 75% of the applied nitrogen was agronomically available (effective rate of ~165 kg N ha^{-1}). This initial rate was used throughout the research period despite subsequent recommendations stating 100% availability of applied nitrogen with a 5% N volatilization loss (Killorn and Lorimor, 2003). Every year, applications of manure (on both corn and soybean) averaged 168 kg N ha^{-1}.

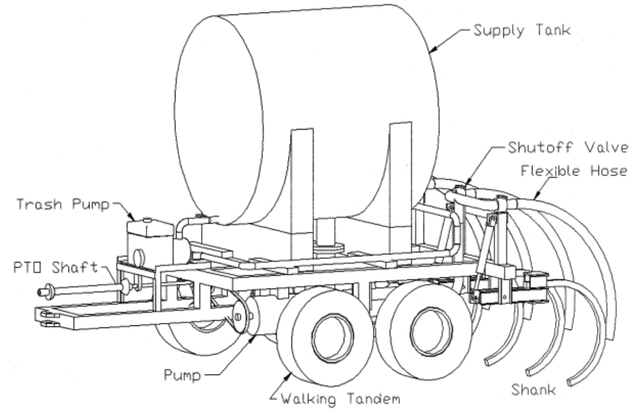

Figure 1. Manure applicator used in the study.

Agronomic field operations were carried out according to local practices and timetables. In all years, a conventional cropping system was used. Fall chisel-plow tillage of corn residue after stalk chopping in the fall was followed by spring disking of both corn and soybean plots with additional seedbed preparation using a field cultivator. Manure plots with manure application prior to both corn and soybeans were not chisel plowed because manure injection was considered primary tillage. Metolachlor (Dual II Magnum, Syngenta Crop Protection, Greensboro, N.C.) at 2.34 L ha^{-1} (2.14 kg a.i. ha^{-1}) was applied and incorporated in all plots pre-emerge, and glyphosate (Roundup UltraMAX, Monsanto Co., St. Louis, Mo.) at 2.04 L ha^{-1} (1.22 kg a.i. ha^{-1}) was applied post-emerge for weed control. Pioneer 92B71 Roundup Ready soybean and Dekalb 545 Roundup Ready corn were used during the study. A two-pass cultivation procedure was used, in addition to herbicides, for weed control. Seeding occurred in the first two weeks of May each year and was typical for the area. Although not typical for the area, the spring fertilizer application timings represented a

Table 1. Nitrogen, phosphorus, and potassium in manure "as applied" application rates (all values are kg ha^{-1}).

	Spring Manure before Corn			Fall Manure before Corn			Fall Manure before Corn and Soy		
Year	N	P	K	N	P	K	N	P	K
2000	--	--	--	205	59	109	156	41	85
2001	207	50	97	239	66	103	174	44	74
2002	230	86	59	222	90	95	140	35	71
2003	221	61	81	225	86	84	155	59	61
2004	194	57	87	--	--	--	--	--	--
Avg.	213	64	81	223	75	98	156	45	73

Table 2. Commercial N application dates, temperatures, and precipitation after N application and freeze/thaw dates.

Application Period	Application Date	10 cm Soil Temperature (°C)	Precipitation before Freezing (mm)	Precipitation between Fall and Spring Applications (mm)	10 cm Freeze Date	10 cm Thaw Date
Fall 2000	14 Nov. 2000	2	5	--	24 Nov. 2000	--
Spring 2001	4 June 2001	16	--	267	--	5 Apr. 2001
Fall 2001	12 Nov. 2001	8[a]	80	--	24 Dec. 2001	--
Spring 2002	21 May 2002	15	--	220	--	4 Apr. 2002
Fall 2002	13 Nov. 2002	3.3	0	--	3 Dec. 2002	--
Spring 2003	5 June 2003	18	--	227	--	15 Mar. 2003
Fall 2003	30 Oct. 2003	7	3	--	27 Nov. 2003	--
Spring 2004	20 May 2004	20	--	280	--	17 Mar. 2004

[a] Slightly warming to 12.6°C then proceeded to drop to below 10°C two days later.

Table 3. Liquid swine manure (LSM) application dates, temperatures, and precipitation after application and freeze/thaw dates.

Application Period	Application Date	10 cm Soil Temperature (°C)	Precipitation before Freezing (mm)	Precipitation between Fall and Spring Applications (mm)	10 cm Freeze Date	10 cm Thaw Date
Fall 2000	27 Oct. 2000	12	64	--	24 Nov. 2000	--
Spring 2001	14 Apr. 2001	9	--	142	--	5 Apr. 2001
Fall 2001	7 Nov. 2001	12	95	--	24 Dec. 2001	--
Spring 2002	16 Apr. 2002	18	--	126	--	4 Apr. 2002
Fall 2002	21 Nov. 2002	4	0	--	3 Dec. 2002	--
Spring 2003	23 Apr. 2003	12	--	100	--	15 Mar. 2003
Fall 2003	20 Nov. 2003	6	3	--	27 Nov. 2003	--
Spring 2004	13 Apr. 2004	8	--	172	--	17 Mar. 2004

Table 4. Corn planting and commercial N spring application dates with precipitation amounts prior to and after application.

Planting Date	Application Date	Precipitation (mm)				
		10 Days Prior	Day 1-10 After	Day 11-30 After	Day 31-60 After	Total 60 Days After
5 May 2000	17 May 2000	17	42	80	139	278
11 May 2001	4 June 2001	20	60	7	114	201
9 May 2002	21 May 2002	13	40	51	31	135
8 May 2003	5 June 2003	9	55	196	107	367
7 May 2004	20 May 2004	25	118	91	69	303

best management practice recommended by numerous researchers (Blackmer et al., 1997, Jaynes et al., 2004; Randall and Mulla, 2001; Dinnes et al., 2002). Locally, most N fertilizer is applied either in late fall or early spring several weeks prior to planting. To determine the crop yield, the middle six rows of the ten rows on each side of the drain tile in the plot were harvested using a three-row combine. The other rows were harvested but yields were not measured since the remaining rows were on the exterior of the plot or essentially right over the tile line. Manual weights for each combine pass were recorded for yield determination. Grain was weighed and sampled to determine moisture content of the grain for each pass. Grain yields were corrected to 15.5% moisture for corn and 13% moisture for soybean.

Commercial N application dates, soil temperatures, and precipitation after fall N application are listed in table 2, and LSM application dates, soil temperatures, and precipitation after application are listed in table 3. Generally, soils in the area froze late November to late December and thawed in mid-March to early April, limiting subsurface drainage to periods when the ground is not frozen. Table 4 lists corn planting dates and precipitation amounts before and after spring N applications.

Results

Weather and Subsurface Drainage

Long-term normal annual precipitation for Pocahontas, Iowa, located 15 km west of the research site, was 784 mm (table 5). Average annual precipitation at the research site during the 2001-2004 research period was 710 mm. Annual precipitation ranged from 680 mm in 2002 (13% below normal) to 767 mm (2% below normal) in 2004. Therefore, all years during the study period were slightly below normal. Precipitation during the drainage season (March to November) was slightly below the long-term norm for all years in the study period and ranged from 614 mm (85% of normal) in 2001 to 706 mm (98% of normal) in 2004. Monthly rainfall was highly variable, and subsurface drainage, or the lack thereof, mimicked the precipitation patterns observed. The majority of fall periods were drier than normal, with no drainage available for monitoring. Annual reference evapotranspiration (ET_o) for 2001-2004 averaged 901 mm, while drainage season ET_o (March to November) averaged 847 mm (table 6). In 2001, soils thawed in early April (tables 2 and 3), and near normal rainfall (table 5) was recorded, resulting in an average of 44 mm of drainage for April (table 7). May 2001 had 179% of the average rainfall, resulting in 168 mm of drainage, the highest

Table 5. Precipitation at the research site.

Month	Precipitation (mm) 2001	2002	2003	2004	2001-04 Average	Long-Term Average[a]
March	16	7	28	97	37	55
April	89	65	79	80	78	81
May	143	77	109	168	124	99
June	68	51	218	98	109	116
July	90	77	147	80	99	110
August	72	262	42	13	97	111
September	40	30	0	88	40	78
October	42	87	0	14	36	57
November	54	1	0	68	31	46
Drainage season (Mar.-Nov.)	614	657	623	706	650	753
Annual	702	680	689	767	710	821

[a] From Climatological Data for Iowa, National Climate Data Center for Pocahontas and Humboldt, Iowa 1971-2000.

Table 6. Reference evapotranspiration in the vicinity of the research site.[a]

Month	Reference Evapotranspiration (mm) 2001	2002	2003	2004	2001-2004 Average
March	23	35	47	41	37
April	107	93	137	140	119
May	119	132	102	137	122
June	155	183	141	125	151
July	133	153	141	120	137
August	109	102	120	96	107
September	57	94	89	119	90
October	67	39	67	52	56
November	41	22	25	26	29
Drainage season (Mar.-Nov.)	810	852	871	856	847
Annual	845	918	928	911	901

[a] Based on Climatological Data from the Iowa Environmental Mesonet Station near Kanawha, Iowa.

Table 7. Average subsurface drainage volumes recorded during individual months for all treatments combined.

Month	Drainage Volume (mm) 2001	2002	2003	2004	2001-2004 Average
April	44	10	34	36	31
May	168	59	91	121	110
June	44	28	142	103	79
July	0	0	91	4	24
August	1	92	0	5	24
September	0	13	0	0	3
October	0	13	0	0	3
November	0	0	0	0	0

of any period due to a delay in drainage water flow or drain flow extending for a period of time. Spring fertilizer was applied after this intense drainage period. A drier summer and early fall period in 2001 was followed by an above-average November through December precipitation pattern. After N application on 12 November 2001 and prior to freezing soil conditions in late December, 80 mm of rainfall was recorded. However, this was not sufficient to cause any subsurface drainage.

Table 8. Average subsurface drainage volume by treatment within years and among years.[a]

Treatment	Drainage Volume (mm) 2001	2002	2003	2004	2001-2004 Average
Fall 168	208 a	216 a	296 a	258 a	245 a
Spring 168	234 a	230 a	327 a	377 a	292 a
Fall 252	284 a	160 a	336 a	264 a	261 a
Spring 252	293 a	264 a	324 a	201 a	271 a
Fall manure 218	241 a	240 a	446 a	296 a	303 a
Spring manure 218	283 a	199 a	426 a	308 a	304 a
Fall manure 168 every year	253 a	180 a	339 a	268 a	260 a
$LSD_{0.05}$	156	160	285	298	100
Average drainage[b]	256 bc	213 c	356 a	280 b	277

[a] Means followed by the same letter within years and on average (i.e., within columns) are not significantly different at p = 0.05.

[b] Means followed by the same letter within the row for average drainage are not significantly different at p = 0.05.

Thawing of the soil on 4 April 2002 (tables 2 and 3) was followed by 29% below-normal precipitation (table 5) in April to July. August had the largest monthly precipitation total during the study period (262 mm) and resulted in an average of 92 mm of subsurface drainage (table 7). September and November precipitation was well below normal. Precipitation in 2003 was slightly above average (table 5) in May and June with rainfall two times the normal (215 mm) average, resulting in June having one of the highest drainage volume months (142 mm) (table 7). ET_o during June 2003 was also below the four-year average for June. Total precipitation within 60 days following spring 2003 application was 367 mm (table 4). No precipitation was recorded from September to November 2003. In 2004, precipitation from March to May was 57% above normal.

Drainage volumes between treatments were not statistically different (table 8). Most drainage (45% to 95%) occurred in April to June of each year, except for 2002 when 55% occurred from August to October. Lawlor et al. (2008) reported that for the period from 1990-2004 on average 86% of drainage at this research site occurred during the April through June period. During the period from 2001-2004 on average 80% of the drainage occurred during the April through June period. Yearly variation in subsurface drainage volumes is to be expected when studying modified natural systems under ambient rainfall conditions. Average annual subsurface drainage volumes were significantly different between years during the study period, even when precipitation totals were similar. For example, with only 9 mm additional precipitation in 2003 versus 2001, there was nearly 100 mm more drainage than in 2001 (wet spring in 2003 and moderate rainfall throughout 2001). In summary, hydrologically two of the four years (2001 and 2004) had substantial drainage periods in the early spring, which would increase the risk of NO_3-N loss for N applied the previous fall since the majority of N uptake by corn would occur after early June (Ritchie et al., 1993). Drier than normal fall through spring periods were encountered in 2001-2002 and during the fall of 2003, which should reduce risk associated with nitrate-N leaching loss.

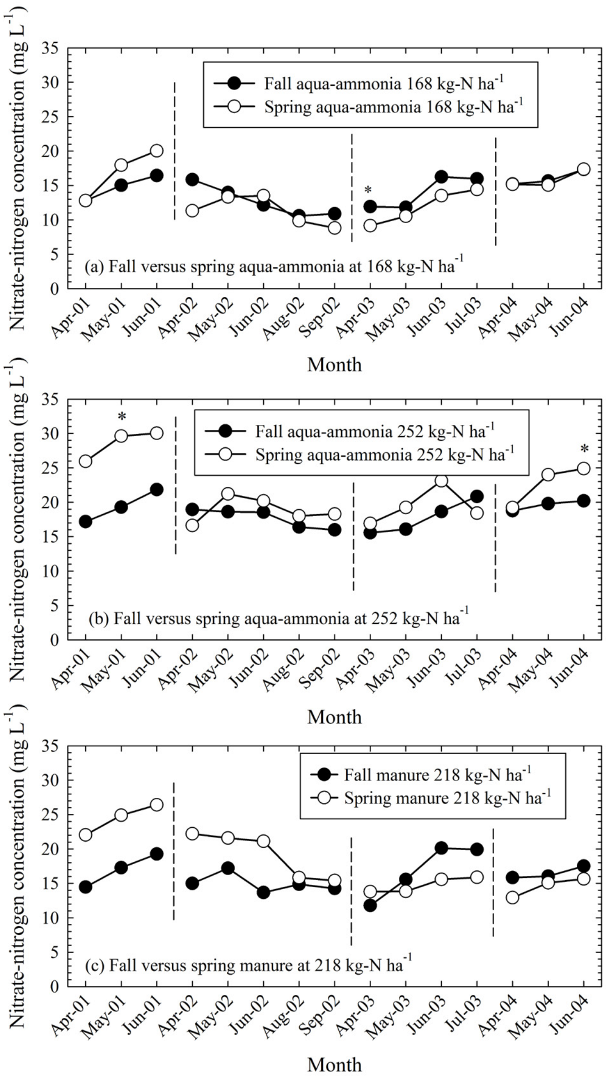

Figure 2. Comparison of monthly flow-weighted nitrate-nitrogen concentrations for spring and fall applications. Values with an asterisk (*) indicate significantly different concentrations for that month at p = 0.10.

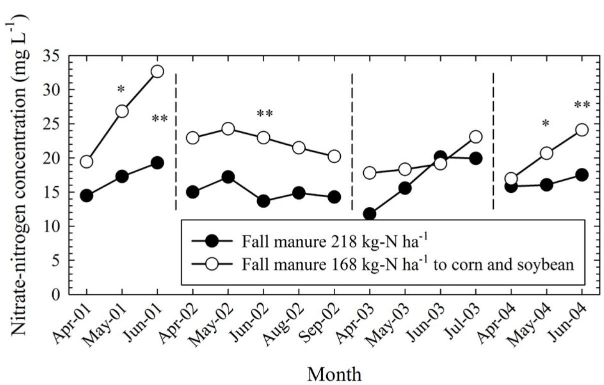

Figure 3. Comparison of monthly flow-weighted nitrate-nitrogen concentrations for fall manure applications on corn only followed by soybean, and corn and soybean. Values with an asterisk (*) indicate significantly different concentrations for that month at p = 0.10. Values with double asterisks (**) indicate significantly different concentrations for that month at p = 0.05.

NITRATE-NITROGEN CONCENTRATIONS IN SUBSURFACE DRAINAGE

Monthly flow-weighted NO_3-N concentrations are shown in figures 2 and 3. The 168 kg ha^{-1} rate of aqua-ammonia applied in the fall had a higher concentration in April 2003 than when applied in the spring, but was similar to the spring application timing at all other dates (p = 0.10) (fig. 2a). However, spring-applied aqua-ammonia at 252 kg ha^{-1} had 5 to 10 mg L^{-1} greater nitrate-N than a fall application in May 2001 and June 2004 (p = 0.10) (fig. 2b). Manure N at 218 kg ha^{-1} in the fall or spring had similar monthly concentrations (fig. 2c). When comparing the treatment where manure was applied prior to corn and soybean to the treatment where manure was just applied to corn, monthly flow-weighted NO_3-N concentrations were 6 to 16 mg L^{-1} higher in May 2001 and May 2004 (p = 0.10) as well as June 2001, 2002, and 2004 (p = 0.05) (fig. 3).

Average annual flow-weighted NO_3-N concentrations ranged from 10.9 (spring aqua-ammonia 168 kg ha^{-1} in 2002) to 29 mg L^{-1} (spring aqua-ammonia 252 kg ha^{-1} in 2001) (table 8). Four-year average flow-weighted NO_3-N concentrations measured in drainage water were ranked: spring aqua-ammonia 252 (23 mg L^{-1}) = fall manure 168 every year (23 mg L^{-1}) > fall aqua-ammonia 252 (19 mg L^{-1}) = spring manure 218 (18 mg L^{-1}) = fall manure 218 (17 mg L^{-1}) > spring aqua-ammonia 168 (15 mg L^{-1}) = fall aqua-ammonia 168 (14 mg L^{-1}). The highest NO_3-N concentrations were observed in spring 2001, a period that had above-normal precipitation preceded by below-normal rainfall and drainage in 2000 (data not presented).

Statistical examination of NO_3-N concentration data from the four-year monitoring periods resulted in no significant differences between the spring and fall application timings except for where the spring aqua-ammonia 252 treatment had greater average NO_3-N concentrations than the fall aqua-ammonia 252 treatment for the four-year monitoring period. The trends were consistent for both the aqua-ammonia and manure N sources. Because manure was applied at 218 kg ha^{-1} and aqua-ammonia was applied at 168 and 252 kg ha^{-1}, exact comparisons of NO_3-N concentrations from manure and commercial N treatments were not possible. However, considering the four-year averages, within the fall-applied applications, NO_3-N concentrations increased with N application rate, no matter the source; the same was true for spring-applied applications. As shown in table 9, some, but not all, of these differences were statistically significant.

Table 9. Flow-weighted NO_3-N concentrations during the thawed period for a corn-soybean rotation from 2001-2004.[a]

	NO_3-N Concentration (mg L^{-1})				
Treatment	2001	2002	2003	2004	2001-2004 Average
Fall 168	14.8 d	11.7 c	14.7 b	15.7 c	14.2 c
Spring 168	18.0 bcd	10.9 c	15.0 b	15.8 c	14.9 c
Fall 252	19.5 bcd	17.4 ab	19.7 ab	19.9 ab	19.0 b
Spring 252	28.7 a	19.3 ab	23.0 a	21.9 a	23.2 a
Fall manure 218	17.0 cd	15.6 bc	18.6 ab	16.0 bc	16.8 bc
Spring manure 218	24.6 abc	18.7 ab	15.0 b	15.1 c	18.4 b
Fall manure 168 every year	26.3 ab	22.5 a	20.2 ab	23.0 a	23.0 a
$LSD_{0.05}$	8.4	5.3	6.3	4.1	3.0

[a] Means followed by the same letter within years and on average are not significantly different at p = 0.05.

Based on these results, it could be concluded that NO_3-N concentrations from LSM were consistent with what would be expected if a similar rate of aqua-ammonia were used. However, this assumes that the N application rate for LSM is based on 100% of total N in the manure. If 75% of total N was considered available for crop utilization and 218 kg N ha^{-1} were applied to supply approximately 163 kg N ha^{-1}, the data suggest the potential for increased NO_3-N concentrations when compared to 168 kg N ha^{-1} of aqua-ammonia. When LSM was applied at 168 kg N ha^{-1} to both corn and soybean, the result was significantly higher NO_3-N concentrations in subsurface drainage when compared to NO_3-N concentrations in drainage from the spring-applied LSM 218 rate. An increase of approximately 35% was observed. Water quality data from lower N rates of LSM on alternative crops (e.g., current manure management rules in Iowa allow LSM to soybean at one-half the nitrogen removal rate of soybean ~112 kg ha^{-1}) are lacking, highlighting the need for additional research.

Nitrate-Nitrogen Losses in Subsurface Drainage

Annual losses of NO_3-N in subsurface drainage by individual treatments and years from 2001-2004 ranged from 25 to 86 kg ha^{-1} (table 10). Losses and NO_3-N concentrations were affected by drainage season precipitation and drainage volume, crop uptake, N application rate, and organic matter mineralization and less so by timing of N application in this research. Approximately 80% of the N losses that occurred in 2001 was prior to spring N fertilizer application on 4 June and was likely derived from organic matter N mineralization and previous fall and spring applications made in a minimal drainage year (2000, data not presented), suggesting residual N and a delay in N loss from the previous season. In 2002, losses were less than those recorded in 2001 and 2003, and more than half the losses occurred between August and October 2002, an atypical loss period. Precipitation and drainage volume patterns from May to June 2003 were the highest recorded during the study, although total seasonal losses were second to those in 2001. Four-year (2001-2004) average kg N ha^{-1} losses were ranked: spring aqua-ammonia 252 = spring manure 218 = fall manure 168 every year = fall aqua-ammonia 252 > spring aqua-ammonia 168 = fall manure 218 = fall aqua-ammonia 168 (table 10). At high rates of N fertilizer (252 kg N ha^{-1}), fall applications resulted in lower losses compared to spring applications in three of four years, which could be a result of denitrification losses or organic matter incorporation, but the differences were not statistically different. Spring manure application losses were on average 9 kg N ha^{-1} higher than fall applied losses, but the differences were not significant.

Table 10. NO_3-N losses during the thawed period for a corn-soybean rotation from 2001-2004.[a]

	NO_3-N loss (kg-N ha^{-1})				
Treatment	2001	2002	2003	2004	2001-2004 Average
Fall 168	32 c	27 a	44 a	41 a	36 b
Spring 168	37 bc	25 a	49 a	58 a	42 b
Fall 252	53 bc	33 a	64 a	49 a	49 ab
Spring 252	86 a	47 a	74 a	49 a	64 a
Fall manure 218	38 bc	33 a	49 a	48 a	41 b
Spring manure 218	70 ab	37 a	46 a	45 a	50 ab
Fall manure 168 every year	58 abc	36 a	50 a	56 a	50 ab
$LSD_{0.05}$	33	24	43	50	17

[a] Means followed by the same letter within years and on average are not significantly different at p = 0.05.

Table 11. Corn yield for 2001-2004.[a]

	Yield (kg ha^{-1})				
Treatment	2001	2002	2003	2004	2001-2004 Average
Fall 168	8199 c	8707 b	8293 ab	10182 c	8845 cd
Spring 168	8871 bc	8364 b	7477 b	10273 bc	8740 d
Fall 252	8277 c	7973 b	7945 b	10283 bc	8619 d
Spring 252	8967 bc	8474 b	8450 ab	11147 ab	9302 c
Fall manure 218	10338 a	10906 a	9232 a	11949 a	10607 a
Spring manure 218	10060 a	10609 a	9227 a	11813 a	10427 a
Fall manure 168 every year	9562 ab	10359 a	7864 b	11570 a	9854 b
$LSD_{0.05}$	958	1006	981	901	488
Pocahontas County average	8485	10046	10542	12260	10333

[a] Means followed by the same letter within years are not significantly different at p = 0.05.

Crop Production

Fall-applied manure at 218 kg ha^{-1} was the highest corn-yielding treatment in all four years (table 11) and was similar to spring-applied manure and fall manure every year except for 2003. A corn yield reduction in the fall manure every year treatment in 2003 compared to the other manure treatments may have been a nitrogen rate response. Fall-applied aqua-ammonia at 168 kg ha^{-1} was similar to a spring application (2001-2004). Similarly, there was no difference in corn yield between fall and spring applied aqua-ammonia at 252 kg ha^{-1} each year, but the four-year average yield was 683 kg ha^{-1} greater when aqua-ammonia was spring applied. Average corn yields for the N management systems were ranked (2001-2004): fall manure 218 = spring manure 218 > fall manure 168 every year > spring aqua-ammonia 252 = fall aqua-ammonia 168 > spring aqua-ammonia 168 = fall aqua-ammonia 252.

Spring-applied manure at 218, spring aqua-ammonia 252, and spring aqua-ammonia 168 had similar soybean yields each year, and the average yield of spring manure at 218 was 320 kg ha^{-1} greater than spring aqua-ammonia 168 (table 12). When soybean yields are averaged over all years, the three

Table 12. Soybean yield for 2001-2004.[a]

	Yield (kg ha^{-1})				
Treatment	2001	2002	2003	2004	2001-2004 Average
Fall 168	2895 c	2829 bc	2020 ab	2913 c	2683 d
Spring 168	3530 ab	3459 ab	2222 ab	3082 abc	3073 b
Fall 252	3006 c	2580 c	1874 b	2890 c	2625 d
Spring 252	3670 ab	3362 ab	2287 ab	3254 abc	3143 ab
Fall manure 218	3175 bc	2916 bc	1881 b	3025 bc	2765 cd
Spring manure 218	3804 a	3620 a	2506 a	3688 a	3393 a
Fall manure 168 every year	3193 bc	3216 abc	2012 ab	3563 ab	2996 bc
$LSD_{0.05}$	499	653	582	612	274
Pocahontas County average	2856	3286	2251	3084	2869

[a] Means followed by the same letter within years are not significantly different at p = 0.05.

fall N treatment yields were lower than spring-applied treatments across both N sources, possibly indicative that nitrogen applied at least 18 months prior to utilization by a soybean crop, as opposed to one year, was missing or diminished to a level that affected production. Nitrogen applied one season prior to the soybean crop apparently remained at levels to benefit the succeeding crop. However, soybean yields when manure was applied before both soybean and corn were not increased, but were intermediate all years and on average to those for manure applied to corn in the fall and the spring.

Summary and Conclusions

During the five years of this study, drainage season precipitation (March-November) was slightly below the long-term norm for all years and ranged from 614 mm (85% of normal) in 2001 to 707 mm (98% of normal) in 2004. Years 2002 and 2003 each had drier than normal fall seasons, and no drainage occurred during these periods. Most drainage occurred between April and June of each year for three of the four years monitored. Hydrologically, the study period had two of the four years with substantial drainage periods in the early spring, when it is expected that most drainage and N losses may occur.

Average annual flow-weighted NO_3-N concentrations ranged from 10.9 (spring aqua-ammonia 168 kg ha^{-1} in 2002) to 29 mg L^{-1} (spring aqua-ammonia 252 kg ha^{-1} in 2001) (table 9). Four-year average flow-weighted NO_3-N concentrations measured in drainage water were ranked: spring aqua-ammonia 252 (23 mg L^{-1}) = fall manure 168 every year (23 mg L^{-1}) > fall aqua-ammonia 252 (19 mg L^{-1}) = spring manure 218 (18 mg L^{-1}) = fall manure 218 (17 mg L^{-1}) > spring aqua-ammonia 168 (15 mg L^{-1}) = fall aqua-ammonia 168 (14 mg L^{-1}). Data showed the highest concentrations (2001) occurred during an above-normal precipitation period preceded by a dry period; both 1999 and 2000 were dryer than the norm. The lowest concentrations during the study were measured in a below-normal precipitation period (2002) following above-normal precipitation the previous year. In all years, for the 168 and 252 commercial N rates and LSM at 218 N rate, no significant differences were noted for concentration when comparing spring and fall application periods. The results were not entirely consistent with those of Randall and Vetsch (2005) and Randall et al. (2003). Randall et al. (2003) found reductions in annual overall average NO_3-N concentrations for the corn year of approximately 12% and an increase of 19% in the soybean years when they applied N in the spring compared to fall (1987-1994). Between 1994 and 2000, concentrations for spring-applied N were 25% less in the corn year and 5% higher in the soybean year when N was applied in southern Minnesota (Randall and Vetsch, 2005). Randall and Vetsch (2005) and Randall et al. (2003) reported overall NO_3-N loss reductions of 14% and 13%, respectively, from the corn-soybean system when N was applied in the spring rather than the fall. However, these researchers also documented that NO_3-N concentration differences were not realized every year. Of note is that Randall et al. (2003) and Randall and Vetsch (2005) studied the corn and soybean phases separately, while this study examined a system with corn and soybean present on each plot in each year. Timing of subsurface drainage was similar between the Randall and Vetsch (2005) study and the study described here, where 71% and 80% of the annual drainage occurred from April through June, respectively. The significantly higher NO_3-N concentration averages for the spring versus fall application periods at the high N rate (252) treatment may be a result of N immobilization or denitrification between the application times in the fall until subsurface drainage carried the N to the drainage lines the following spring. Although timing, method of N application, and accounting for mineralizable soil N are important for reducing potential NO_3-N leaching, this research would tend to support conclusions reached by Power and Schepers (1989) that perhaps the most important factor was to apply the correct amount of N.

When LSM was applied prior to both corn and soybean at a rate of 168 kg N ha^{-1}, NO_3-N concentrations were higher (36%) in subsurface drainage then when LSM was applied at 218 kg N ha^{-1} to corn only in rotation. The increase in NO_3-N concentrations observed in this study were less than observed by Bakhsh et al. (2009), where an 80% increase in NO_3-N concentrations was observed when manure was applied at 174 and 219 kg N ha^{-1} to both corn and soybean, respectively. Overall, results highlight that there is a potential risk of increased NO_3-N concentrations if LSM is applied prior to both corn and soybean. However, the N application rate to the soybean crop was higher in this study than is currently allowed in Iowa, and more studies are needed on NO_3-N leaching impacts when soybean is used as a receiver crop for land application of LSM at lower nitrogen application rates.

NO_3-N losses ranged from 25 to 86 kg-N ha^{-1}. Four-year (2001-2004) average kg N ha^{-1} losses were ranked: spring aqua-ammonia 252 = spring manure 218 = fall manure 168 every year = fall aqua-ammonia 252 > spring aqua-ammonia 168 = fall manure 218 = fall aqua-ammonia 168. Losses and NO_3-N concentrations in this study were predominantly affected by drainage season precipitation timing and application rate and less so by N application timing.

The two highest overall average yields for corn during the study were recorded for the 218 kg N ha^{-1} manure treatments (spring and fall timings) and were significantly higher than all other commercial N treatments and the manure every year treatment. Manure treatments out-yielded commercial N in all years. No significant differences in corn yield for any year were noted between application timing when comparing equal rates and fertilizer form; however, on average, spring 252 out-yielded fall 252. Soybean yields were affected by N timing and less so by application rate. When soybean yields were averaged over all years, the three fall N treatment yields were lower than spring-applied treatments across both N sources, possibly indicative that nitrogen applied 18 months prior to utilization by a soybean crop was missing or diminished to a level that affected production. This multi-year experiment demonstrated that rate and to a lesser extent timing affect concentration and losses; even at constant rates, concentration and losses can be highly variable depending on precipitation patterns, N mineralization/denitrification processes, and crop utilization in a given season.

References

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water

requirements. Irrigation and Drainage Paper No. 56. Rome, Italy: United Nations FAO.
Baker, J. L., and S. W. Melvin. 1994. Chemical management, status and findings. In *Agricultural Drainage Well Research and Demonstration Project: Annual Report and Project Summary*, 27-60. Des Moines, Iowa: Iowa Department of Agriculture and Land Stewardship.
Bakhsh, A., R. S. Kanwar, J. L. Baker, J. Sawyer, and A. Mallarino. 2009. Annual swine manure applications to soybean under corn-soybean rotation. *Trans. ASABE* 52(3): 751-757.
Balkcom, K. S., A. M. Blackmer, D. J. Hansen, T. F. Morris, and A. P. Mallarino. 2003. Testing soils and cornstalks to evaluate nitrogen management on the scale of watersheds. *J. Environ. Qual.* 32(3): 1015-1024.
Blackmer, A. M., R. D. Voss, and A. P. Mallarino. 1997. Nitrogen fertilizer recommendations for corn in Iowa. Pm-1714. Ames, Iowa: Iowa State University Extension Service.
Bundy, L. G. 1986. Timing nitrogen applications to maximize fertilizer efficiency and crop response in conventional corn production. *J. Fert. Issues* 3(3): 99-106.
Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron. J.* 94(1): 153-171.
Gilliam, J. W., J. L. Baker, and K. R. Reddy. 1999. Water quality effects of drainage in humid regions. Agronomy Monograph No. 38. Madison, Wisc.: ASA, CSSA, SSSA.
Jaynes, D. B., D. L. Dinnes, D. W. Meek, D. L. Karlen, C. A. Cambardella, and T. S. Colvin. 2004. Using the late spring nitrate test to reduce nitrate loss within a watershed. *J. Environ Qual.* 33(2): 669-677.
Kanwar, R. S., T. S. Colvin, and D. L. Karlen. 1997. Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. *J. Prod. Agric.* 10(2): 227-234.
Killorn, R., and J. Lorimor. 2003. Managing manure nutrients for crop production. Pm-1811. Ames, Iowa: Iowa State University Extension Service.
Lawlor, P. A., M. J. Helmers, J. L. Baker, S. W. Melvin, and D. W. Lemke. 2008. Nitrogen application rate effect on nitrate-nitrogen concentration and loss in subsurface drainage for a corn-soybean rotation. *Trans. ASABE* 51(1): 83-94.
Mitsch, W. J., J. W. Day Jr., J. W. Gilliam, P. M. Groffman, D. L. Hey, G. W. Randall, and N. Wang. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River basin: Strategies to counter persistent ecological problem. *Bioscience* 51(5): 373-388.
Power, J. F., and J. S. Schepers. 1989. Nitrate contamination of groundwater in North America. *Agric. Ecosyst. Environ.* 26(3-4): 165-187.
Rabalais, N. N., W. J. Wiseman, R. E. Turner, B. K. Sen Gupta, and Q. Dortch. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. *Estuaries* 19(2): 386-407.
Randall, G. W., and D. J. Mulla. 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. *J. Environ. Qual.* 30(2): 337-344.
Randall, G. W., and M. A. Schmitt. 1998. Advisability of fall-applying nitrogen. In *Proc. 1998 Wisconsin Fert., Aglime, and Pest Mgmt. Conf.*, 90-96. Madison, Wisc.: University of Wisconsin.
Randall, G. W., and J. A. Vetsch. 2005. Nitrate losses in subsurface drainage from a corn soybean rotation as affected by fall and spring application of nitrogen and nitrapyrin. *J. Environ. Qual.* 34(2): 590-597.
Randall, G. W., D. R. Huggins, M. P. Russelle, D. J. Fuchs, W. W. Nelson, and J. L. Anderson. 1997. Nitrate losses through subsurface tile drainage in Conservation Reserve Program, alfalfa, and row crop systems. *J. Environ. Qual.* 26(5): 1240-1247.
Randall, G. W., J. A. Vetsch, and J. R. Huffman. 2003. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by time of nitrogen application and use of nitrapyrin. *J. Environ. Qual.* 32(5): 1764-1772.
Ritchie, S. W., J. J. Hanway, and G. O. Benson. 1993. How a corn plant develops. Spec. Rep. 48 (revised). Ames, Iowa: Iowa State University Extension Service.
SAS. 2009. *SAS/STAT User's Guide.* Version 9.2. Cary, N.C.: SAS Institute, Inc.
Sawyer, J. E., A. P. Mallarino, R. Killorn, and S. K. Barnhart. 2002. A general guide for crop nutrient and limestone recommendations in Iowa. Pm-1688. Ames, Iowa: Iowa State University Extension Service.
Schmidt, J. P., M. A. Schmitt, G. W. Randall, J. A. Lamb, J. H. Orf, and H. T. Gollany. 2000. Swine manure application to nodulating and nonnodulating soybean. *Agron. J.* 92(5): 987-992.
Schmitt, M. A., D. R. Schmidt, and L. D. Jacobson. 1996. A manure management survey of Minnesota swine producers: Effect of farm size on manure application. *Applied Eng. in Agric.* 12(5): 595-599.
Schmitt, M. A., G. W. Randall, M. P. Russelle, and J. A. Lory. 1998. Progressive manure management to minimize negative environmental impact of nitrogen. In *1998 Agronomy Abstracts.* Madison, Wisc.: ASA.
USDA-SCS. 1992. Chapter 11. In *Agricultural Waste Management Field Handbook*. Washington, D.C.: USDA Soil Conservation Service
Vetsch, J. A., and G. W. Randall. 2004. Corn production as affected by nitrogen application timing and tillage. *Agron. J.* 96(2): 502-509.
Weed, D. A. J., and R. S. Kanwar. 1996. Nitrate and water present in and flowing from root-zone soil. *J. Environ. Qual.* 25(4): 709-719.
Zhu, Y., and R. H. Fox. 2003. Corn-soybean rotation effects on nitrate leaching. *Agron. J.* 95(4): 1028-1033.